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A measurement of the Λ_c^+ lifetime

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A precise measurement of the Λ_c^+ lifetime using approximately 1500 fully reconstructed $\Lambda_c^+ \to pK^-\pi^+$ and charge conjugate decays is presented. The data were accumulated by the Fermilab high energy photoproduction experiment E687. The lifetime of the Λ_c^+ is measured to be $0.215\pm0.016\pm0.008$ ps.

The lifetime of the Λ_c^+ charmed baryon is poorly measured compared to those of the D^0 and D^+ charmed mesons. This is partly due to the relatively lower production rate for charmed baryons and partly due to poorer reconstuction efficiency because of the shorter lifetime of the Λ_c^+. This paper reports a new measurement of the Λ_c^+ lifetime using approximately 1500 fully reconstructed $\Lambda_c^+ \to pK^-\pi^+$ decays. Throughout this paper, the charge conjugate state is implied when a decay mode of a specific charge is stated. Previous measurements have been limited to samples of ≈ 100 or fewer Λ_c^+ decays. Due to the relatively large sample of Λ_c^+ decays, extensive consistency checks of the results and a detailed systematic study can be made. An accurate measurement of the Λ_c^+ lifetime is important in order to understand the contribution of the W-exchange mechanism to the weak decay process [1].

The data for this analysis were collected in 1990 and 1991 in the Fermilab wideband photoproduction experiment E687. About 500 million triggers were recorded on tape during this period. The E687 detector is described in detail elsewhere [2].

The Λ_c^+ decays were reconstructed by a method based on the presence of a downstream vertex. It is a *candidate driven* method where all candidate $pK^-\pi^+$ combinations are initially assumed to form a secondary vertex. A candidate Λ_c^+ *seed* track, formed from the sum of the daughter momentum vectors, is used to search for a primary vertex. The primary vertex is reconstructed by searching for tracks which form high confidence level intersections with the seed track. All track parameter errors are properly taken into account. The efficiency of this algorithm in finding vertices is essentially independent of the primary and secondary vertex separation, and so this method should not create a bias in the lifetime measurement.

A number of cuts were used to select $pK^-\pi^+$ combinations. Each of the decay secondaries must be reconstructed in both the microstrip and multiwire proportional chamber systems, and the two sets of track parameters must agree within measurement errors. Information from the Čerenkov counters is used to select protons, kaons and pions.

The three microstrip tracks of the $pK^-\pi^+$ combination forming the secondary vertex are required to extrapolate back to a single point with a confidence level greater than 1%. This confidence level of the secondary vertex will be labeled *CLD*. The confidence level that any of the three $pK^-\pi^+$ tracks extrapolate back to the primary vertex is labeled *CL1*. The confidence level that other microstrip tracks not already assigned to either the primary or secondary vertices point back to the secondary vertex is labeled *CL2*. The number of background $pK^-\pi^+$ combinations can be greatly reduced by cuts on *CL1* and *CL2*. The drawback is that these cuts can induce a small proper time dependence on the efficiency of vertex reconstruction. We require that the secondary vertex lie upstream of the first scintillator trigger counter, which is upstream of the first microstrip plane. This accomplishes two things. It reduces systematic effects due to inefficient track reconstruction for charmed particles decaying within the microstrip system and it allows a more reliable Monte Carlo simulation of the experimental trigger. A reliable Monte Carlo simulation is important when cuts are made on *CL1* and *CL2*, as a Monte Carlo correction is necessary to correct the proper time dependence of the vertex reconstruction efficiency. The final important cut is the significance of detachment of the primary and secondary vertices. We use the variable ℓ/σ_ℓ, where ℓ is the signed three dimensional separation between the primary and secondary vertices, and σ_ℓ is the error on ℓ computed on an event by event basis taking into account the effects of multiple Coulomb scattering.

Figure 1 shows $pK^-\pi^+$ invariant mass plots for various cuts on *CLD*, *CL1*, *CL2* and ℓ/σ_ℓ. It can be seen the signal-to-noise can be improved by increasingly harder cuts on *CLD*, *CL1* and *CL2*, (compare Fig. 1(c) with Figs. 1(a) and (d)), or for given *CLD*, *CL1* and *CL2* cuts, by a harder cut on ℓ/σ_ℓ, (compare Fig. 1(a) and (b)). The Λ_c^+ yields presented with the figures are determined from fits to the mass distributions to a Gaussian peak over a linear background.

The method used to measure the Λ_c^+ lifetime is very similar to the one we used to measure the D^0 and D^+ lifetimes [4]. We fit to the *reduced proper time*. The reduced proper time is given by $t' = (\ell - N\sigma_\ell)/\beta\gamma c$, where N represents the significance of detachment cut ($\ell/\sigma_\ell > N$), and $\beta\gamma$ is the laboratory frame Lorentz boost of the Λ_c^+. To the extent that σ_ℓ is independent of ℓ (as data and Monte Carlo studies show), the t' distribution for Λ_c^+ decays will be of the form $\exp(-t'/\tau)$, where τ is the lifetime of the Λ_c^+.

A fit is made to the t' distribution for events within $\pm2\sigma$ of the Λ_c^+ mass, (approximately ±20 MeV/c^2), using a *binned* maximum likelihood method. Two reduced proper time histograms are made: one for events within $\pm2\sigma$ of the Λ_c^+ mass, (the *signal histogram*); and one for events within two sidebands, each 4σ wide, above and below the Λ_c^+ mass, (the *sideband histogram*). The observed number of events within a reduced proper time bin (centered at t'_i) for the signal histogram is labeled s_i, and for the sideband histogram is labeled b_i. The expected number of events (n_i) in the signal histogram for reduced proper time bin i is given by

$$n_i = S\frac{f(t'_i)e^{-t'_i/\tau}}{\sum f(t'_i)e^{-t'_i/\tau}} + B\frac{b_i}{\sum b_i}, \tag{1}$$

where $S = \sum s_i - B$ is the total number of signal events in the signal histogram, B is the total number of background events in the signal histogram, and $f(t'_i)$ is a correction function. Fifty time bins are used to span five nominal lifetimes. The fit parameters are τ and B.

The function $f(t')$, derived from Monte Carlo simulation, corrects the signal lifetime distribution for effects of acceptance, analysis cut efficiencies, hadronic absorption and decay of the charm secondaries. Fig. 2 shows plots of $f(t')$ for the Λ_c^+ samples shown in Fig. 1. The size of the variations of $f(t')$ with t' depend on the actual cuts made on *CLD*, *CL1*, *CL2* and ℓ/σ_ℓ. Comparison of the measured lifetimes for these samples will show the reliability of the $f(t')$ correction function used. As a consistency check of the background lifetime evolution (b_i) used in the fit, different sidebands are used, at 4σ, 6σ and 8σ from the Λ_c^+ mass.

In order to tie the value of B to the background level expected from the mass sidebands, we include an additional factor in the likelihood function. The background level is thereby jointly determined from the invariant mass plot and the lifetime evolution. The final likelihood function is given by

$$L = \prod \frac{n_i^{s_i}e^{-n_i}}{s_i!} \times \frac{(2B)^{N_b}e^{-2B}}{N_b!}, \tag{2}$$

where $N_b = \sum b_i$.

Simulations where care was taken in modeling the background lifetime evolution revealed both the presence of a small bias in the lifetime fitting procedure, and a slight underestimation of the true statistical error due to the neglected fluctuations in b_i. The fitting bias is found to be ≈ 0.005 ps and the statistical error is found to be underestimated by $\approx 15\%$. The lifetime results are corrected for this fitting bias and the statistical error bars from the fits are corrected to include contributions from fluctuations in b_i.

For a consistency check of the measured lifetime, two variations of this method are also used for comparison. In the first, we use an *event by event* method where the likelihood function is calculated from the product of the probabilities for each event [5]. In the second variation of the maximum likelihood fit method, the *absolute proper time* is used instead of the reduced proper time. The absolute proper time is given by $t = \ell/\beta\gamma c$. The disadvantage of using the absolute proper time is that a much larger $f(t)$ correction is needed at short proper times because of the cut on ℓ/σ_ℓ. However, it provides another consistency check on the reliability of the $f(t')$ correction used.

Figures 3(a)–(c) show the measured Λ_c^+ lifetimes plotted versus the ℓ/σ_ℓ cut for the three different sets of cuts on *CLD*, *CL1* and *CL2* shown in Fig. 1. The *binned maximum likelihood* fit method with the *reduced* proper time is used. The measured lifetimes using the *absolute* proper time, and using the *event likelihood* method are shown in Figs. 3(d) and (e) respectively. It can be seen that all the results are very consistent with each other and no significant variation with respect to the ℓ/σ_ℓ cut is seen.

Figure 4 shows the background subtracted and $f(t')$ corrected reduced proper time distributions for the four Λ_c^+ samples shown in Fig. 1. The superimposed curve is a pure exponential function using the Λ_c^+ lifetime found by the fit. In choosing the ℓ/σ_ℓ, *CLD*, *CL1* and *CL2* cuts at which to quote the lifetime, we are guided by the principle of maintaining a reasonable signal to noise while keeping the statistical error to a minimum. We will quote the lifetime at the cuts used for Fig. 1(a). The lifetime is 0.215 ± 0.016 ps.

Further consistency checks are made on the measured lifetime. The fitted lifetime could show a possible dependence on variations of the background proper time distribution. Different sidebands are used in the fit to check this. Background from the decays D^+ and $D_s^+ \to K^+K^-\pi^+$, where the K^+ is misidentified as a proton, could cause problems in the lifetime measurement. As a check on this, the lifetime was measured for two Λ_c^+ samples where this background contamination is significantly reduced. In one sample, the proton had to be identified by the Čerenkov counters as defintely a proton, (*i.e.* not allowing protons identified as K/p ambiguous), and in the other sample D^+ and D_s^+ decays are eliminated by eliminating events where the $K^+K^-\pi^+$ mass is within ± 24 MeV of the D^+ mass or within ± 30 MeV of the D_s^+ mass. The contamination due to $D^+ \to K^-\pi^+\pi^+$ decays, where one of the pions is misidentified as a proton, is negligible. The fitted lifetime may also be sensitive to the assumed momentum distribution of the Λ_c^+ particles. To check this the Λ_c^+ sample is split into a low ($p < 100$ GeV/c) and a high ($p \geq 100$ GeV/c) momentum sample, and the lifetime is measured separately for these two samples. Additionally, the total Λ_c^+ sample is split into particle and anti-particle samples, and into data taken in 1990 and 1991 as further consistency checks of the measured lifetime. Figure 5 shows a comparison of the measured lifetimes for all these different samples for a single ℓ/σ_ℓ cut of $\ell/\sigma_\ell > 4$. Again, it is evident that the results are all very consistent with each other and that any systematic errors in the measured lifetime are small compared to the statistical error.

Although the systematic error on the measured lifetime is seen to be small compared to the statistical error, an upper limit on the systematic error can be estimated.

Due to uncertainties in the target absorption corrections, we include a systematic error of 0.002 ps for the Λ_c^+ lifetime. Two effects are present: hadronic absorption of the decay secondaries, if not corrected for, will tend to give a larger fitted Λ_c^+ lifetime, and absorption of the Λ_c^+ by the target material prior to decay will tend to give a lower Λ_c^+ lifetime. Uncertainties in the secondary absorption correction arise because we are uncertain of the extent to which elastic scattering of the secondaries causes severe mismeasurement of the parent Λ_c^+. The Λ_c^+ absorption cross section is unknown. By varying the Λ_c^+ absorption cross section between zero and two times the proton-nuclear cross-section, the variation of the fitted Λ_c^+ lifetime is only 0.003 ps. We take the Λ_c^+-nuclear cross-section to be the proton-nuclear cross-section for the absorption correction.

We ascribe a systematic error of 0.005 ps for the uncertainty in the $f(t')$ correction function used. This is obtained by looking at variations of the fitted lifetime when the $f(t')$ correction function is varied within its statistical error as given by the Monte Carlo, and by looking at the variations when different cuts on *CLD*, *CL1*, *CL2* and ℓ/σ_ℓ are used.

A systematic error of 0.005 ps is included for uncertainties in the background lifetime distribution under the signal peak. This is determined by looking at variations in the fitted lifetimes using different background sidebands, and by looking at differences in the fitted lifetimes for the two Λ_c^+ samples, mentioned previously, where background from D^+ and D_s^+ decays have been significantly reduced.

The acceptance of the charm secondaries depends partly on the Λ_c^+ momentum. Higher momentum charm particles will, on the average, decay nearer the microstrip system than low momentum ones, and thus have a larger acceptance. Also, charm particles produced near the edge of the experimental target have a slightly smaller acceptance than those produced at the center of the target because their decay secondaries have a larger probability of laying outside the transverse fiducial volume of the first microstrip station. These two effects depend on the assumed momentum spectrum and the beam profile, and due to uncertainties in these we add an additional systematic error of 0.002 ps.

For uncertainties in the correction for fit biases in the fitting method used, we include a systematic error of 0.003 ps. This includes uncertainties due to the choice of the number of time bins used and the maximum lifetime cut used. This is obtained by looking at variations in the lifetime using the other two fitting methods, variations in the fitted lifetime when different numbers of time bins are used and variations in the fitted lifetime when different maximum reduced proper time cuts are used.

Combining all sources of systematic errors incoherently, we obtain a final Λ_c^+ lifetime measurement of 0.215 ± 0.016(*statistical*)± 0.008(*systematic*) ps.

In summary, we report on a new measurement of the Λ_c^+ lifetime based on a sample of $\approx$ 1500 fully reconstructed $\Lambda_c^+ \to pK^-\pi^+$ decays. The measured lifetime is 0.215 ± 0.016(*statistical*)± 0.008(*systematic*) ps. The data satisfy many consistency checks, and extensive systematic studies were made.

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FIG. 1. Λ_c^+ signals for various cuts on *CLD*, *CL1*, *CL2* and ℓ/σ_ℓ used in the lifetime analysis. The fit masses are within 2.5 MeV/c^2 of the current world averages [3] and the widths of the signals are consistent with our experimental resolution.

FIG. 2. The deviation from a pure exponential decay, $f(t')$, computed from Monte Carlo simulations for the four Λ_c^+ samples shown in Fig. 1. The fits shown on the plots are to a linear form.

FIG. 3. (a), (b) and (c) Results of lifetime fits as a function of the ℓ/σ_ℓ cut for different sets of cuts on *CLD*, *CL1* and *CL2*. (d) Results of lifetime fits using the absolute proper time. (e) Results of lifetime fits using the event likelihood fit method. Both the lifetimes and statistical errors have been corrected for the background effects as described in the text.

FIG. 4. The background subtracted and Monte Carlo corrected lifetime evolution measured for the four Λ_c^+ samples shown in Fig. 1.

FIG. 5. A comparison of measured lifetimes for different sidebands used in the binned maximum likelihood fit, and for different Λ_c^+ samples described in the text.

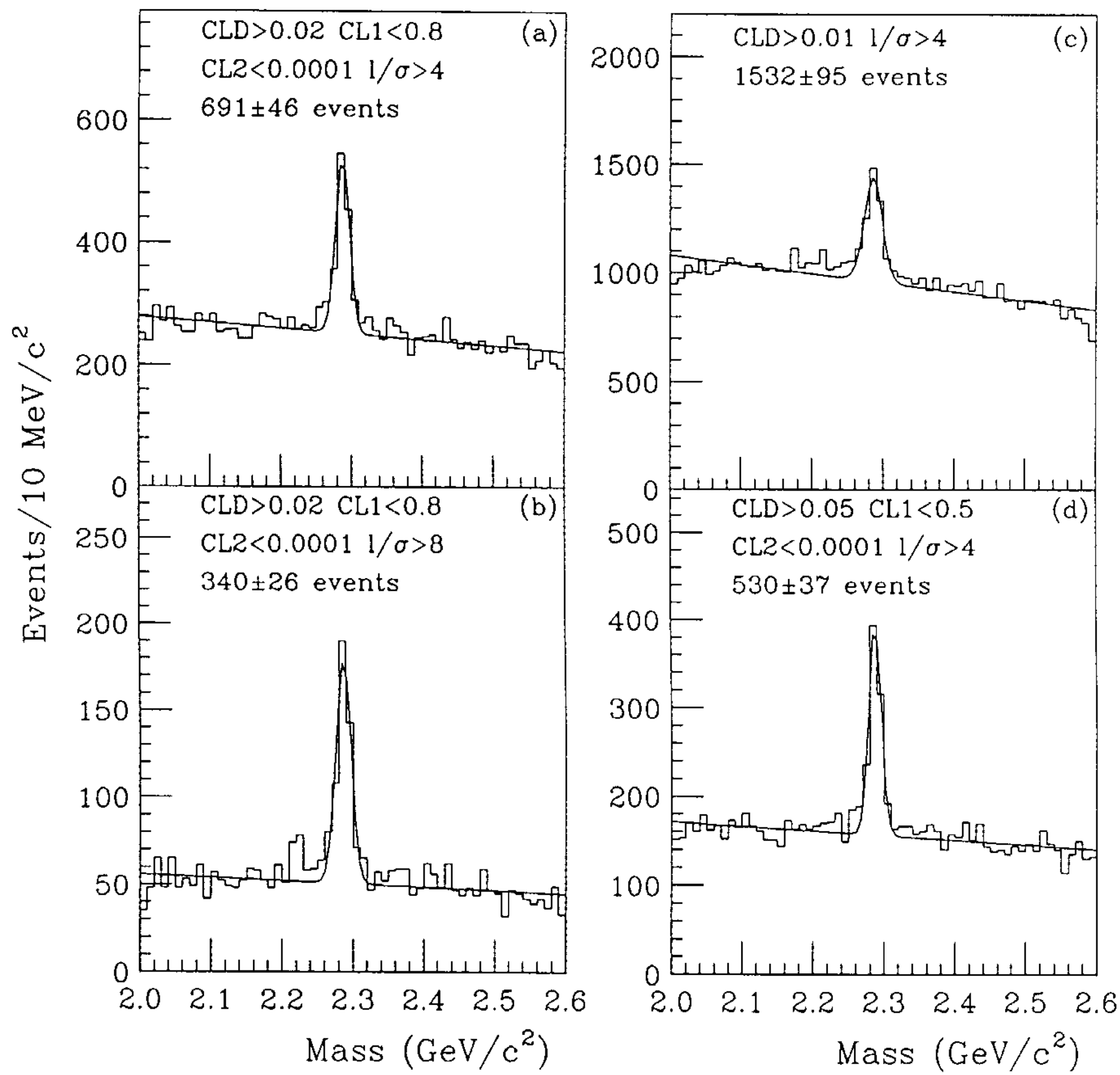
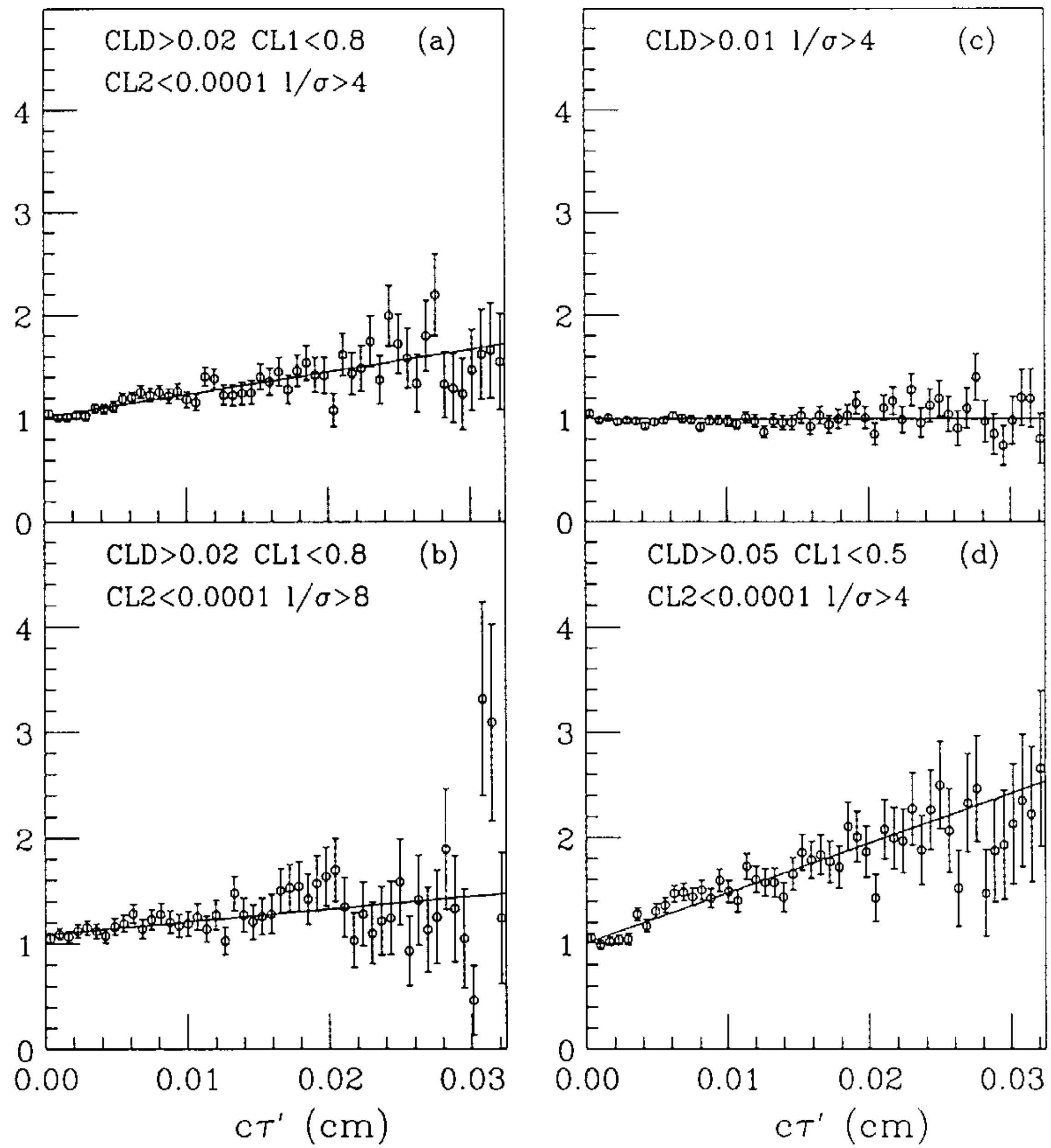

CLD>0.02 CL1<0.8
CL2<0.0001 l/σ>4
691±46 events
(a)
CLD>0.02 CL1<0.8
CL2<0.0001 l/σ>8
340±26 events
(b)
CLD>0.01 l/σ>4
1532±95 events
(c)
CLD>0.05 CL1<0.5
CL2<0.0001 l/σ>4
530±37 events
(d)
Events/10 MeV/c²
Mass (GeV/c²)
Mass (GeV/c²)

Figure 1.



CLD>0.02 CL1<0.8 (a)
CL2<0.0001 l/σ>4
CLD>0.01 l/σ>4 (c)
CLD>0.02 CL1<0.8 (b)
CL2<0.0001 l/σ>8
CLD>0.05 CL1<0.5 (d)
CL2<0.0001 l/σ>4
0
1
2
3
4
0.00
0.01
0.02
0.03
cτ' (cm)

Figure 2.

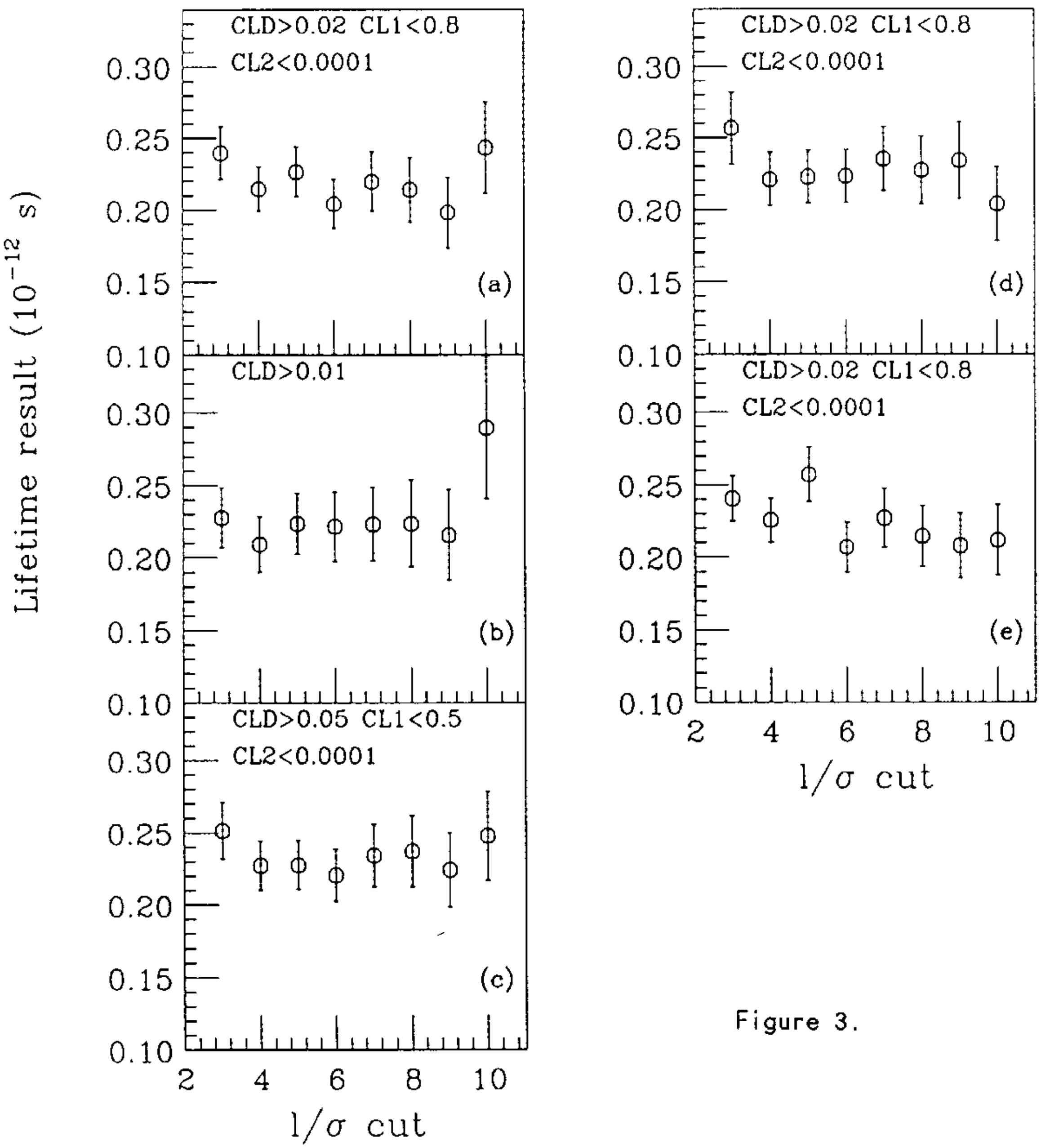
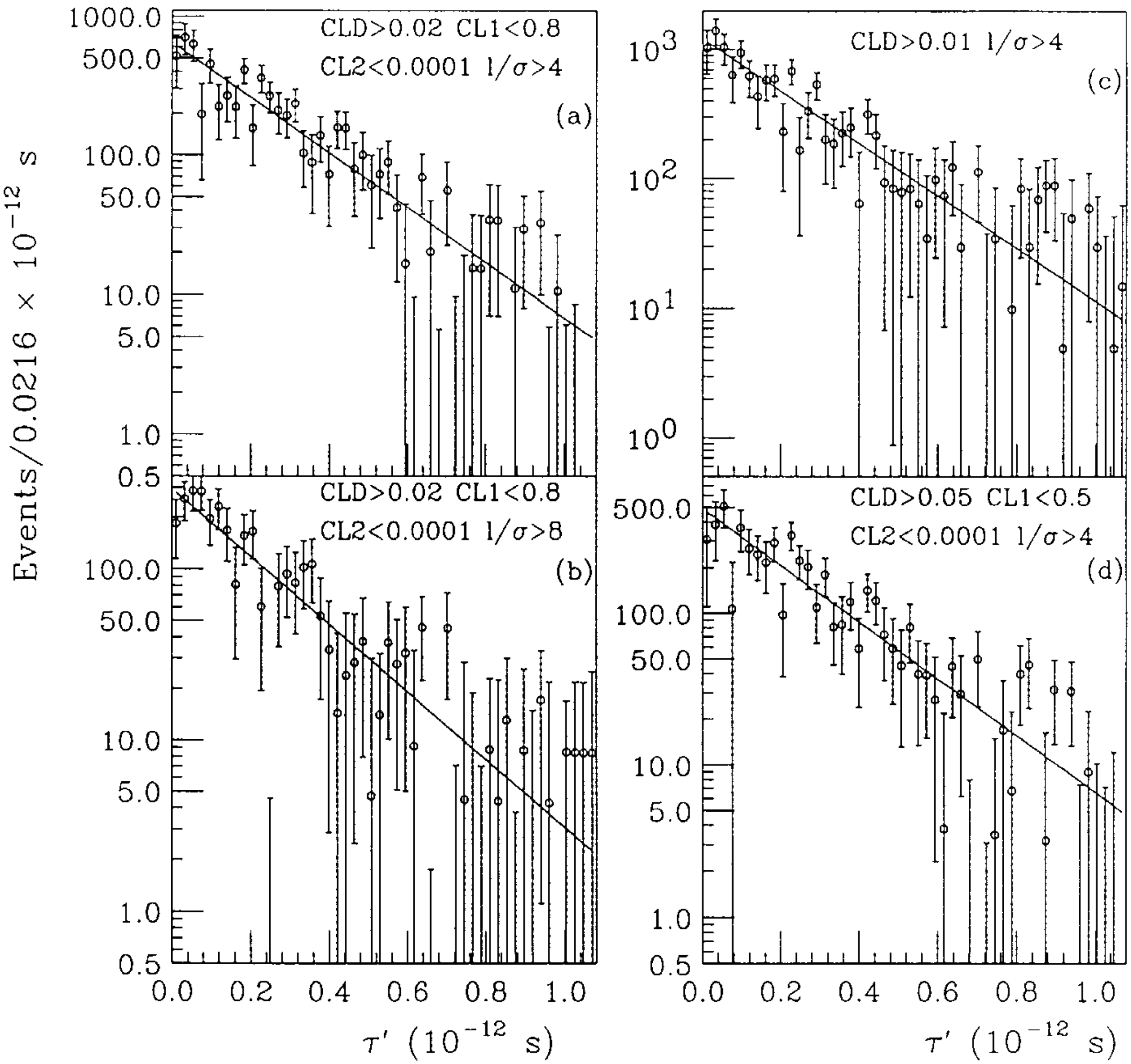
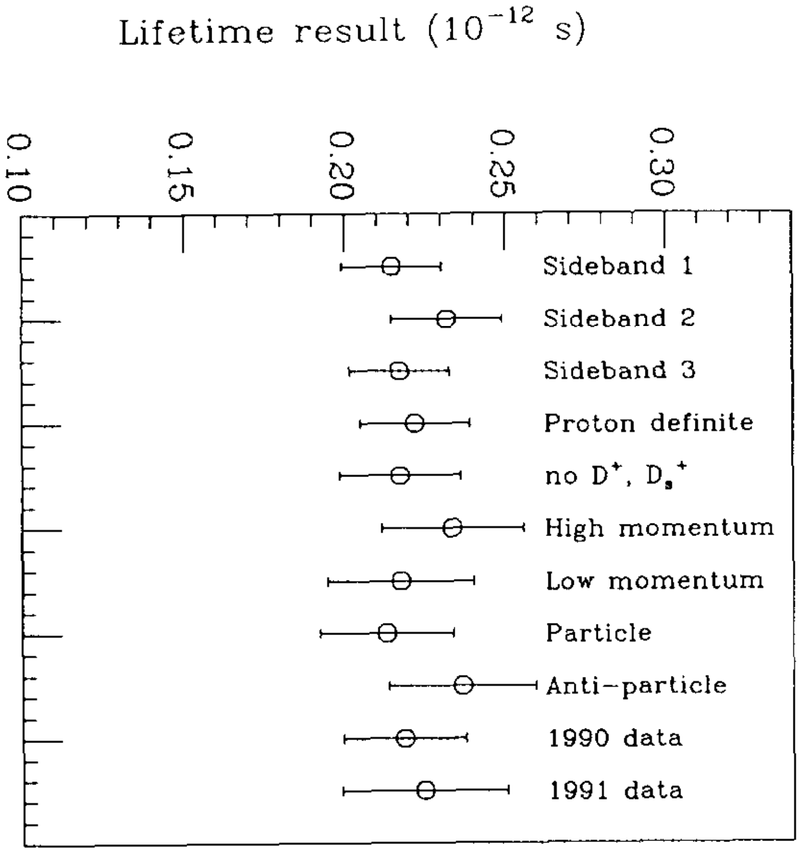

Lifetime result (10^{-12} s)
CLD>0.02 CL1<0.8
CL2<0.0001
(a)
CLD>0.01
(b)
CLD>0.05 CL1<0.5
CL2<0.0001
(c)
CLD>0.02 CL1<0.8
CL2<0.0001
(d)
CLD>0.02 CL1<0.8
CL2<0.0001
(e)
0.10
0.15
0.20
0.25
0.30
2
4
6
8
10
l/σ cut

Figure 3.



Events/0.0216 × 10^-12 s
CLD>0.02 CL1<0.8
CL2<0.0001 l/σ>4
(a)
CLD>0.02 CL1<0.8
CL2<0.0001 l/σ>8
(b)
CLD>0.01 l/σ>4
(c)
CLD>0.05 CL1<0.5
CL2<0.0001 l/σ>4
(d)
τ' (10^-12 s)
τ' (10^-12 s)

Figure 4.



Lifetime result (10^{-12} s)
0.10
0.15
0.20
0.25
0.30
Sideband 1
Sideband 2
Sideband 3
Proton definite
no D^+, D_s^+
High momentum
Low momentum
Particle
Anti-particle
1990 data
1991 data

Figure 5.